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Global value chain assessment based on retrospectively induced economic costs associated with technology application: A case study of photovoltaic power system in Japan

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ABSTRACT

Global warming is a worldwide problem that requires an international strategy to ensure compatibility of economic growth and overcoming climate change. Although global use of low-carbon technology is a solution, consideration of economic consequences is important to promote future technology development and use. Photovoltaic (PV) solar power system is a promising renewable technology that carries climate mitigation expectations. We conducted a value chain analysis to evaluate the economic effect of the manufacture and use of silicon PV solar power system worldwide. We quantitatively reviewed the flow of manufacturing and installation for cells, modules, and facilities (e.g., inverters) related to Japan, and estimated the retrospectively induced economic costs for Japan and other developed and developing countries. Material, equipment, labor, utility, transportation, and business operation costs were studied in detail at different manufacturing and installation stages. This unique evaluation methodology quantified economic costs from an international perspective. The retrospectively induced economic effect of 2014 PV solar power system sales in Japan (induced by cell module and system production by Japanese companies and increased domestic use) was 1.6 trillion Japanese yen worldwide, of which 63% was attributable to Japan, 10% to other developed countries, and 27% to developing countries. The economic effect in Japan in terms of equipment cost and installation stage was 37% and 71% of the total effect, which was particularly high. Further technical improvement, cost reduction, and improvement in inverter and manufacturing equipment reliability are important to capitalize Japan's strengths. Currently, Japan's involvement in the manufacturing of cells and modules is small. Therefore, both technical innovation and cost reduction are necessary. We present new methodology to obtain inputs into policy development for further research, development, and technology diffusion.

1. Introduction

Global warming must be mitigated as a common issue worldwide. Energy conservation and renewable energy technologies have multifaceted significance in reducing emissions. The importance of technology diffusion has been well-recognized by experts studying climate change. The United Nations Framework Convention on Climate Change continues efforts to stabilize atmospheric greenhouse gas concentration and adapt to impacts. Discussions on the framework beyond 2020 (when the Kyoto Protocol commitment period is over) have started. At the end of 2015, the 21st annual Conference of the Parties (COP21) adopted the Paris Agreement, which includes the following points in its decisions (MOE, 2015):

- Maintain the global average temperature increase after the Industrial Revolution within 2 °C and aim to limit the increase to 1.5 °C.
- All countries should submit or update reduction targets every five years and report their implementation in a common and flexible way for review.
- Utilization of market mechanisms that directly relate to the global division of decarbonizing opportunities.
- Importance of innovation.

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Nomenclature

C	Cost
C_{RIEC}	Retrospectively induced economic cost through the value chain
Q	Quantity of flow in the value chain (solar cell/module sales [W] between stages)
R	Ratio of retrospectively induced economic effect to each region
U	Unit cost (cost/W), cost divided by PV power output
CP	Suffix for Cell production stage
MP	Suffix for Module production stage
DS	Suffix for Distribution stage
IN	Suffix for Installation stage
mt	Suffix for material
eq	Suffix for equipment
lb	Suffix for labor
tr	Suffix for transportation and shipment
bs	Suffix for business profit and operation
$main$	Suffix for main equipment
Jp	Suffix for Japan
Os	Suffix for overseas
$Os\text{-}ic$	Suffix for overseas (other industrialized countries)
$Os\text{-}dc$	Suffix for overseas (developing countries)
r	Regions (Japan, other developed countries, or developing countries)
f	flow of stages/regions
i	Material
j	Equipment
JPY	Japanese Yen

The Japanese Intended Nationally Determined Contribution states that the target of greenhouse gas emissions by fiscal year (FY) 2030 should be 26.0% less than the FY 2013 level. The section on international contributions mentions that Japan's contribution to reducing greenhouse gas emissions through technology dissemination, including products and services, to developing countries would be quantitatively evaluated. To achieve Japan's reduction targets, a Joint Crediting Mechanism, one of the market mechanism schemes, will be utilized and expected to reduce emissions of 50–100 million tons of CO_2 in total by 2030. For other international contributions, it anticipates that “emission reduction potential in FY 2030 through the diffusion of leading technologies by Japanese industries' actions is estimated to be at least 1 billion t-CO_2.” (UNFCCC, 2015) In addition, it also includes contributions “internationally toward, inter alia, human resource development and promotion of development and diffusion of technologies relating to emission reductions in developing countries.” Together with the decision of the Paris Agreement, it can be said that the scheme or methodology to review, monitor, and verify the reduction of emissions and energy use is significant. Moreover, it is important to understand how to institutionally and financially promote the technology diffusion and transfer worldwide. The UN “2030 Agenda for Sustainable Development” adopted in September 2015 emphasized that the use of funds will become increasingly important and that various resources are required for sustainable development in developing countries, including official development assistance, domestic funds, and private funds.

Central to this is how we promote and use technology at a global level and cooperate for this purpose. We previously proposed an Integrated Contribution Approach (ICA) focused on promoting and transferring energy and environmental technologies as an effective way to reduce greenhouse gas (Tanaka et al., 2016). This may hold merits and opportunities for both developed and developing countries by quantifying the contribution to climate mitigation, promoting private investment incentives, and establishing a mechanism for business opportunities in the host country's economic development (Fig. 1). This is consistent with the concept confirmed in the Paris Agreement as well as the 2030 Agenda, as described above.

Although technology is central to solutions to worldwide problems such as climate change, the wide spread of technology requires a framework in which technology is spontaneously used in economic and development activities, rather than based on regulations and obligations. It is of the utmost importance to promote private investment incentives and to establish a mechanism to utilize various business opportunities for the host country's economic development. In considering such a framework, it is important to understand the regional economic impacts that accompany multilateral technical use, as discussed in this study. We evaluated the benefits of technology use to a target area on a global scale, with the aim of acquiring useful information to contribute to a framework to promote global technology development and use and identifying future possibilities for technology in the global market.

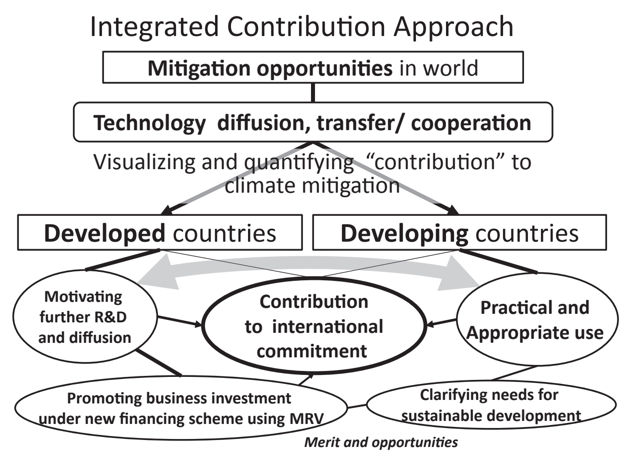

Fig. 1. Scope and objectives of the Integrated Contribution Approach.

To achieve this, we performed value chain analysis based on the cost structure to evaluate economic effects by manufacturing and use of a photovoltaic (PV) system technology. We focused on a photovoltaic (PV) solar power generation system that is expected to be a means of climate change mitigation. The PV system has been massively diffused at different levels of scale due to a sharp drop in cost in recent years, and it was expected that the annually introduced PV capacity would rapidly peak at 200 GW per year by 2050 (IEA, 2014). Companies in Japan and Germany had the largest share in PV market until 2000 in the developmental stage. During the diffusion stage, production companies were shifted to emerging countries such as China, Korea, and Taiwan. Because the PV major companies have been dramatically shifted, it is unclear which region the actual benefit belongs to. The objective of this research was to clarify the benefits of the area. Therefore, technologies that have become widespread on such a scale have been broadly procured, and a large influence on dissemination of cost reduction is

preferable as objects of this research.

From studies performed thus far, it remained difficult to analyze the position in the entire market and the regional characteristics of a production site, despite available methodologies that use input–output tables to evaluate economic activity. An input–output table covers the whole economic activity, meaning it is suitable for evaluating the overall picture of the target country. Attempts have been made to expand the input–output tables, and a previous study constructed a hybrid input–output table combining detailed industry sectors related to solar power generation for specialized materials and products (Mizumoto et al., 2013; Krishnan et al., 2008). Attempts have also been made to combine input–output tables for Japan and the US (Cabinet Secretariat, 2013). However, technology is influenced by international markets and technology trends, and it is necessary to examine domestic and overseas spread and retroactive effects on the supply chain to analyze a specific product. The value chain analysis is a novel evaluation beyond an individual country's boundaries that was necessary to evaluate the economic impact on a specific region. It has been used to assess industry and market trends. Although these objects are restricted due to data and other constraints, they are suitable for understanding inter-industry relationships and social structures. Su (2013) and Zhang and Gallagher (2016) reviewed the evaluation in the value chain for the PV industry and analyzed the trends and developments over the years. Besides PV, several papers have discussed analyses related to the value chain (Zhao et al., 2014; Baumert et al., 2016; Le and Wang, 2017; Gregg et al., 2017; Da Silva Guabrioba et al., 2017). These papers are aimed at the future development of the targeted industries and technologies, considering the dynamics including future of the industry and have deep insights regarding the social and industrial structure. However, these capture the value chain as a range where industries have an influence and where technology is used, and therefore just add an international perspective. From the viewpoint of technology transfer, there is also research that has added a value chain perspective. (Lundquist, 2003; Kimura et al., 2005; Chen, 2005; Kuijpers and Swinnen, 2016). These studies were based on approaches from economic and mathematical models that enabled the evaluation of the dynamics of technology transfer. Furthermore, they examined financial costs and ownership aimed at promoting technology transfer, but are not based on specific technical details and do not see the influence as a result of the global procurement of technology. For the analysis of the value chain described above, the manufacturing process was divided, and each region was taken into consideration in this research.

The focus in previous studies so far has been on technical and economic evaluation. In short, they evaluated the final product, but not each individual technology, and region-specific strength and issue. Various information sources are available for the economic evaluation of PV technology, including market analysis reports based on actual sales prices (IEA-PVPS, 2016), manufacturers' annual reports, technical development goals (ITRPV, 2017), future perspectives (Vartiainen et al., 2015), and reports on the evaluation of current costs (BNEF, Chung et al., 2015). It is suitable for evaluating actual prices, price differences in each region, and price trends. However, these sources only evaluated the economics of the final products. Conversely, the impact of cost reduction in cost benefit analyses is evaluated from cost structure analysis. For example, Powell et al. (2012) identified the cost structure and cost reduction potential of c-Si PV using a bottom-up cost model. Goodrich et al. (2013) evaluated the manufacturing cost of the United States and China from the difference in the production scale and the unit price by region. Inoue et al. (2017) subdivided the cost structure analysis into manufacturing equipment in further detail and disassembled manufacturing technology. However, they designed a model plant assuming the place of production and calculating the manufacturing cost. Therefore, it is possible to evaluate the technology in detail; however, it does not take into consideration the production site, specific materials, and components in the actual market. Based on these facts, we used cost structure analysis data on specific technical details and conducted a value chain analysis with regionality in each case. We used the values from the cost structure analysis of crystalline silicon (Si) solar cells conducted by Inoue et al. (2017) to evaluate manufacturing technology as a bottom-up cost analysis and evaluated the economic impact on the targeted area by economic activities in an integrated manner. This allowed evaluation of the economic impact on the target area. With this calculation method, we quantitatively examined technology transfer from the perspectives of technological development, strategic reinforcement in innovation, and problems to be overcome. This may also be an effective method to quantitatively examine the degree of contribution of technology to climate mitigation in a context where technology use on a global scale is promoted and progressed, as described in our proposed ICA.

2. Value chain evaluation methodology

Using a silicon PV power generation system as an example, we evaluated the economic effect of manufacturing and application through the value chain, based on the flow of cells, modules, and peripheral equipment (e.g., inverters) in terms of solar cell capacity. First, we prepared a flow chart of the production volume by classifying the domestic distribution volume of the cell and module by production area or the companies' national origin. Production location information was then given to each element of the manufacturing cost structure. Based on these calculation results, we evaluated the degree of economic impact of technology by region.

The range of the value chain was manufacturing, distribution, and installation. Based on this value chain, we estimated economic impacts in Japan and internationally by region, using the results of a detailed cost analysis for each manufacturing process. Data from Inoue et al. (2017) were used for the cost analyses for preparation of solar grade silicon (SOG-Si), cell and module manufacturing, as that study provided a detailed analysis of manufacturing process at the equipment level, meaning equipment and raw materials for each process could be evaluated individually. In addition to manufacturing costs (Inoue et al., 2017), we calculated business profit and operation expenses (i.e., company operation and maintenance costs). We also considered distribution and installation stages and calculated retrospectively induced economic costs using new detailed material categories for major materials. The influence by region was determined using information such as trade statistics for each cost.

2.1. Cost calculation boundaries

The economic effects of the value chain were calculated for Si monocrystalline and Si polycrystalline solar cells. The value chain was divided into cell production, module production, and installation, considering distribution from cell production to module manufacture and module production to installation. Cell production includes processes for SOG-Si manufacturing, ingot casting, wafer manufacturing, and cell manufacturing. We did not consider the disposal and recycling stages. We focused on three targeted areas: Japan, developed countries other than Japan, and developing countries. The PV system cost was divided into material costs, equipment costs, utility costs, labor costs, business profits and operation expenses, and transportation costs, and calculated for

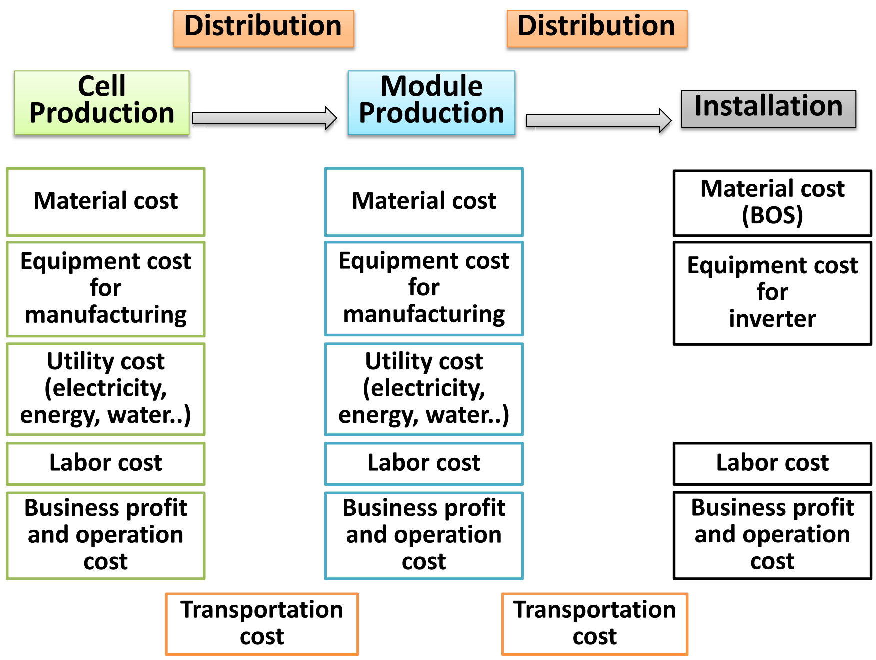

Fig. 2. Costs at each stage of the value chain.

each targeted area (Fig. 2).[1] In each stage, the location of the economic impact differed depending on whether the manufacturing company/manufacturing location/shipping place was Japan or another country. Table 1 summarizes the patterns examined in this study.

2.2. Concept and definition of retrospectively induced economic cost

Manufacturing and distribution of solar cells have various costs at different stages. We defined cost as "the economic effect retrospectively induced in connection with the diffusion of solar cells" and differentiated this from the "induced effect" in an input–output analysis. The relational expressions used for cost calculation are summarized below. The C_{RIEC} reflects how much the cost retrospectively occurred in the value chain when the product was shipped and used. The method of allocating retrospective costs to each region by each cost (R) is explained in detail in 2.4.

$$C_{RIEC} = \sum C_{CP} + \sum C_{MP} + \sum C_{DS} + \sum C_{IN} \tag{1}$$

$$C_{CP} = C_{mt_1} + C_{eq_1} + C_{ut_1} + C_{lb_1} + C_{bs_1} \tag{2}$$

$$C_{MP} = C_{mt_2} + C_{eq_2} + C_{ut_2} + C_{lb_2} + C_{bs_2} \tag{3}$$

$$C_{IN} = C_{mt_3} + C_{eq_3} + C_{lb_3} + C_{bs_3} \tag{4}$$

$$C_{DS} = C_{tr} \tag{5}$$

$$C_{mt} = \sum_{i,r} C_{mt}(i,r) = \sum_{i,\,r,f} \{U_{mt}(i) \times Q(f) \times R_{mt}(i,r)\} \tag{6}$$

$$C_{eq} = \sum_{j,r} C_{eq}(j,r) = \sum_{j,r,f} \{U_{eq}(j) \times Q(f) \times R_{eq}(j,r)\} \tag{7}$$

$$C_{ut} = \sum_{r} C_{ut}(r) = \sum_{r,f} \{U_{ut} \times Q(f) \times R_{ut}(r)\} \tag{8}$$

$$C_{lb} = \sum_{r} C_{lb}(r) = \sum_{r,f} \{U_{lb} \times Q(f) \times R_{lb}(r)\} \tag{9}$$

$$C_{bs} = \sum_{r} C_{bs}(r) = \sum_{r,f} \{U_{bs} \times Q(f) \times R_{bs}(r)\} \tag{10}$$

$$C_{tr} = \sum_{r} C_{bs}(r) = \sum_{r,f} \{U_{tr}(r) \times Q(f)\} \tag{11}$$

2.3. Research flow

The research flow is shown in Fig. 3. This study was divided into three parts: development of a database on quantities of domestic and oversea cell and module flow (Q); setting cost per output power of PV (U); and setting the ratio of C_{RIEC} to each region (R).

Notes

(1) Based on Inoue et al. (2017) (U_{mt}, U_{eq}, U_{ut}, U_{lb}).
(2) For U_{mt} with a high percentage of system costs, the cost was divided into raw material and investigated production areas.
(3) Equipment was entered as a product in the evaluation system boundary and not broken down into material costs.

[1] Custom and corporate taxes also have economic impacts. However, while Japan is free to import solar cells, there are high tariffs for anti-dumping, anti-subsidies for products produced in China, and tax incentives applied to products from other countries in Europe and the US. In addition, corporate taxes and tax incentives vary from region to region, and trade taxes by country and region further complicate the situation. Therefore, we did not consider taxes in this study.

Table 1
Combination of manufacturing companies, manufacturing places, and shipping destinations examined at each stage of the value chain.

Stage	Manufacturing company	Manufacturing place	Shipment
Cell production	Japanese company	Japan	
		Overseas	
	Overseas company	Japan	
		Overseas	
Module production	Japanese company	Japan	
		Overseas	
	Overseas company	Japan	
		Overseas (shipment to Japan only)	
Transportation	Japanese company	Japan	Japan
			Overseas
		Overseas	Japan
			Overseas
	Overseas company	Japan	Japan
			Overseas
		Overseas	Japan
Installation	Japanese company		Japan
			Overseas
	Overseas company		Japan

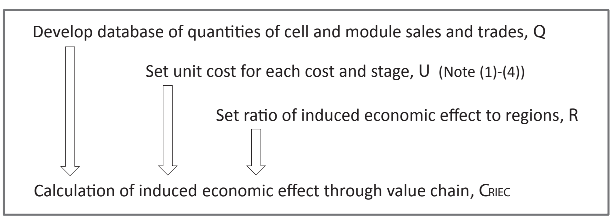

Fig. 3. Research flow.

Equipment includes “equipment for manufacturing” and inverters (power conditioners) at the installation stage.

(4) Newly calculated here are costs for business profit and operation and transportation.

2.3.1. *Development of database on quantity of flow in the value chain (Q)*

For this calculation, we used data on amount of solar cell/module shipment and import/export in 2014 from the published dataset (JPEA, 2017). Some categories are missing from the original database of the JPEA because these are not aimed at showing quantitative flows in a value chain. Therefore, we filled this gap by restructuring the available data according to a category that was necessary for evaluation in this study.

2.3.2. *Calculation of unit cost (U)*

Inoue et al. (2017) calculated manufacturing cost at the equipment level in detail for each process from SOG-Si production to module production of Si solar cells, and showed the costs for raw materials and components. We used specifications for monocrystalline and polycrystalline Si solar cells based on 2012 technology (Table 2). Table 3 shows the material, equipment, utility, and labor costs used in this study, based on calculations by Inoue et al. (2017) and the raw material costs we calculated.

2.3.2.1. Material cost (U_{mt}). As shown in Table 3, we selected materials accounting for 1% or more of the total system cost. Of the selected materials, those with a cost ratio of 2% or more returned to the main raw materials further upstream. Mainstream raw materials were set with reference to actual prices. Figs. 4 and 5 show the target process (stage) and target raw materials. Materials and components shown in purple boxes are those that are directly input in each process. Raw materials targeted upstream are shown in red boxes. For raw material cost calculation, we multiplied consumption by weight unit price. Raw material consumption is indicated by the unit cost per rated output (W) of each module for every process.

Table 2
Basic specifications for a photovoltaic system used for calculations.

Monocrystalline, module conversion efficiency	17%
Poly crystalline, module conversion efficiency	14%
Cell size	156 mm
Module area	1.3 m^2
Production plant scale	1 GW
Annual power generation output	1000 kWh/kW

2.3.2.2. Equipment cost (U_{eq}), utility cost (U_{ut}), and labor cost (U_{lb}). Equipment costs included equipment for manufacturing and inverters (power conditioners) including peripheral electrical appliances used at the installation site. Manufacturing equipment included all factory equipment such as manufacturing equipment, peripheral equipment, installation costs, and factory setup. It does not include equipment for installation (e.g. crane). For utility expenses, we used an electricity cost of 12 JPY/kWh. Labor cost was based on 4 million JPY/year and treated as constant regardless of production location.

2.3.2.3. Business profits and operation expenses (U_{bs}). Inoue et al. (2017) calculated all manufacturing and installation costs as they focused on technology development. However, sale price should be considered when evaluating corporate activity and economic impact. We calculated company profit and operational costs (excluded in the previous study) assuming as 20% of the total cost (not value added cost). This was only applied to solar cell/module manufacturers and installers, as raw material costs used actual prices and included profit and operation expenses.

2.3.2.4. Transportation costs (U_{tr}). We used home logistic values from domestic cell manufacturing to module manufacturing for both Japan and overseas. We assumed that intermodal movement of cell modules was maritime transport, with domestic shipping used for module shipments. We set the ratio of sales amount (cost and business profits/operation expenses) for private logistics and regular transport for Japan, developing countries, and developed countries (Table 4) as follows. According to JILS (2015), the transportation cost for sales of electrical and precision equipment in Japan is about 2%, of which the home logistics consumption is about 0.5%. Based on this, we set Japan's home logistics cost at 0.5% of sales and shipping costs for module product shipment (domestic cost) at 1.5%. The value for China was used as the reference for developing countries and that for the US as the reference for developed countries. JILS (2015) reported that the overall average in Japan was 6.13% (2012) and that in the US was 7.87%; therefore, we assumed that the logistics cost for other developed countries was 7.87%/6.13% = 1.28 times of that of Japan. The shipping cost was 15%–25% of sales in China (CFLP, 2014), and we estimated the logistics cost of developing countries was 15%/6.13% = 2.4 times of that of Japan. Anderson and Wincoop (2004) published a detailed report on international shipping costs. They reported that in the US, the representative value of freight cost in international transportation was 10.7% of the costs, with 5.7% of costs being machinery and transport machinery (6.8% of sales in accordance with the definition used in the present study). Therefore, we set the marine transportation cost as 4.3% of sales.

Table 3
Raw material, utility, equipment, and labor costs used for calculation: monocrystalline silicon (polycrystalline silicon). *Based on the database developed by* Inoue et al. (2017)*; newly added values marked as (*).*

Stage	Materials/components	Unit cost (1000JPY/t)	Material cost, U_{mt} (JPY/W)	*Cost proportion (%)*	Breakdown Note 1), 3)	(*)Unit cost (1000JPY/t)	(*)Material cost, U_{mt} (JPY/W)	Utility cost, U_{ut} (JPY/W)	Equipment cost, U_{eq} (JPY/W)	Labor cost, U_{lb} (JPY/W)
Cell production	Solar grade silicon	3100	3.9 (4.0)	*2.6 (2.4)*	Metal Si	300	3.5 (3.6)	9.7 (9.9)	9.9 (10.3)	0.7 (0.8)
					HCL	15	0.08 (0.09)			
					Hydrogen gas	20(JPY/Nm^3)	0.25 (0.26)			
	Wafer: quartz crucible	1500	5.3 (3.1)	*3.5 (1.9)*	Silica sand	7.3	0.03 (0.02)	4.3 (1.9)	7.3 (6.5)	2.7 (1.7)
					Others		5.2 (3.0)			
	Wafer: silicon carbide (SiC) abrasive grain	500	5.2 (6.3)	*3.5 (3.8)*	Silica sand	7.3	0.37 (2.3)			
					Coke	8	0.31 (0.38)			
					Others		4.5 (5.5)			
	Wafer: piano wire	1000	2.3 (2.8)	*1.5 (1.7)*						
	Wafer: others		1.4 (1.7)	*0.95 (1.0)*						
	Wafer: Total	14 (14)	*9.5 (8.4)*							
	Silver paste for electrodes	80000	3.7 (4.5)	*2.5 (2.7)*	Silver	72000	3.3 (4.0)	1.0 (1.2)	4.5(5.4)	1.4 (1.7)
					Others		0.37 (0.45)			
	Al paste for electrodes	5000	1.5 (1.8)	*1.0 (1.1)*						
	Others		2.3 (2.8)	*1.6 (1.7)*						
	Electrodes and other: Total	7.5 (9.1)	*5.0 (5.5)*							
Module production	Tempered glass	300	14 (17)	*10 (10)*	Silica sand	7.3	0.17 (0.21)	0.1 (0.2)	4.0 (4.7)	0.5 (0.6)
					Soda ash	28	0.21 (0.26)			
					Others		14 (17)			
	Al frame	500	3.7 (4.5)	*2.5 (2.7)*	Aluminum ingot	270	2.0 (2.4)			
					Others		1.7 (2.1)			
	Sealant	400	2.6 (3.2)	*1.7 (1.9)*						
	Back sheet (Polyvinyl fluoride)4)	4000	3.6 (4.3)	*2.4 (2.6)3)*						
	Back sheet (Aluminum)	4000	1.9 (2.3)	*1.2 (1.4)*						
	Others		5.6 (6.8)	*3.7 (4.1)*						
	Total	32 (38)	*21 (23)*							
Installation	Balance of Systems: Steel	250	11 (11)	*7.5 (8.2)*	Iron ore	6	0.40 (0.49)		40 (40)	22 (27)
					Coal	8	0.29 (0.35)			
					Others		10 (13)			

Notes
1) Detailed breakdown of source materials when the cost ratio was 2% or more.
2) Notation up to two decimal places; therefore, the totals of the numbers in the table may not be consistent.
3) "Others" includes the utility cost, labor cost, and equipment cost for production of source materials which are brought into the production stages in this calculation.
4) Although the cost ratio of the polyvinyl fluoride film back sheet is 2% or more, it is a fluorine resin material, which is a chemical product, meaning no further material breakdown is seen.

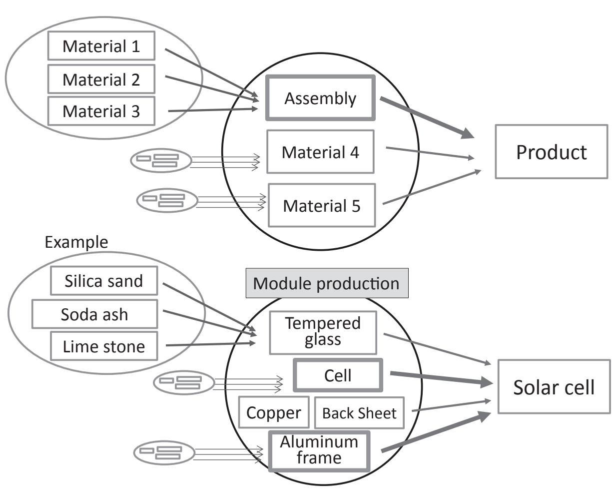

Fig. 4. Approach used for raw material costs calculations.

2.3.3. *Places where economic benefits occurred, (R)*

We used the method shown below to determine whether the costs described in the previous section occurred in Japan, developed countries other than Japan, and/or developing countries (i.e., where the economic effect retroactively occurred).

2.3.3.1. Material/components costs (R_{mt}). We investigated major manufacturers and import sources for each raw material based on trade statistics from Japan's Ministry of Finance and Fuji Keizai (2010a, 2010b, 2012, 2014, 2015), and *R*, ratio of C_{RIEC} to each region, was set (Table 5). We set the regional cost allocation using the volume of production and trade of materials and components. In cases where the manufacturing location was Japan, we assumed domestic demand would be preferentially satisfied if domestic demand or production and supply volume was larger than domestic demand; in cases of less production, the amount of shortage would be imported from overseas. When the manufacturing location was overseas, we assumed R in two different ways. For Japanese companies, in the case there is an overabundance of material for PV production, the remaining material is assumed to be primarily used in other countries. In the other case and overseas companies, we used the proportion of developing and developed countries excluding Japan.

2.3.3.2. Equipment costs (R_{eq}). In manufacturing facilities, procurement areas are differentiated between specific manufacturing equipment (main equipment) and other facilities such as peripheral equipment (pipe, pump, and heat exchanger). The C_{eq} includes building cost of facilities too. Table 6 summarizes the breakdown of the equipment cost shown in the study by Inoue et al. (2017). In this paper, we use different *R* for U_{eq} of main equipment, $U_{eq,main}$, and

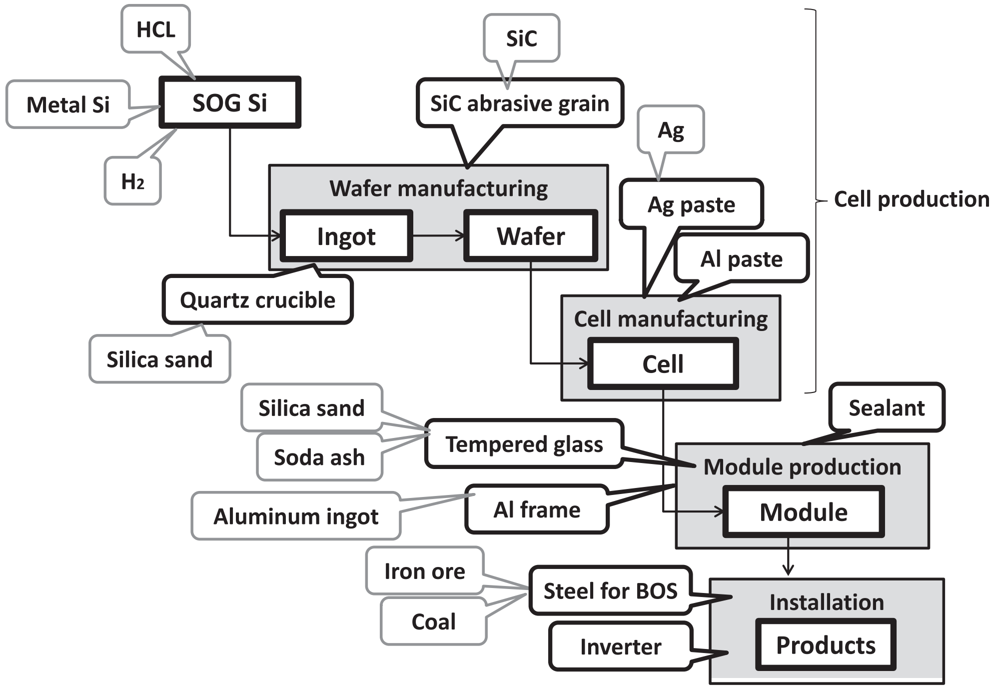

Fig. 5. Main raw materials covered in cost estimates.

Table 4
Transportation expenditure ratio to sales amount used for calculation.

		Percentage of sales amount (%)
Home logistics (Assuming a narrow range movement)	Japan	0.5
	Developing countries	1.2
	Other developed countries	0.6
Marine transport		4.3
Normal transport	Japan	1.5
	Developing countries	3.7
	Other developed countries	1.9

other costs including peripheral equipment and facility building costs using the ratios derived from the numbers in Table 6.

For $U_{eq,main}$ of cell and production, individually;

$$U_{eq,main,\ CP} = U_{eq,\ CP} \times 0.55 \tag{12}$$

$$U_{eq,main,\ MP} = U_{eq,\ MP} \times 0.64 \tag{13}$$

For main equipment at the manufacturing stage (corresponding to $U_{eq,main}$) and inverters (power conditioners) at the installation stage, the R was set based on the area with reference to manufacturing company data for each equipment (Fuji Keizai, 2015). Other cost in the manufacturing stage were assumed to be from manufacturing place.

2.3.3.3. Utility costs, (R_{ut}). When the manufacturing country was Japan, R of Japan accounted for 100% of Japan. For other countries, the ratio of industrialized countries to developing countries was calculated from the production capacity of each plant in each region of reference (Fuji Keizai, 2015).

2.3.3.4. Labor costs, (R_{lb}). For manufacturing companies in Japan, R of Japan accounted for 100% of Japan. For other countries, the ratio of industrialized to developing countries was calculated from the production capacity of each plant in each region of reference (Fuji Keizai, 2015). For the installation stage, the labor cost was considered to occur at the installation site.

2.3.3.5. Business profits and operation expenses, (R_{bs}). If the manufacturing company was a Japanese company, R was 100% for Japan. For other countries, the ratio of developed to developing countries was calculated from the production volume of the companies' head office locations (Fuji Keizai, 2015). For the installation stage, this occurred at the installation site.

2.3.3.6. Transportation costs, (R_{tr}). Costs were considered to have occurred at places where the transportation took place. The cost of marine transport was charged to origin.

3. Results and discussion

3.1. Quantitative flow from production to sale of PV solar power system (case study: Japan)

With reference to statistical data for shipping (JPEA, 2017), the flow of PV power systems in 2014 for the cell manufacturing, module manufacturing, and distribution stages was divided into domestic and overseas. Fig. 6 shows the whole flow including not only silicon type but also others like thin-film solar cells. The module sales (shipment) volume in Japan in the 2014 fiscal year was 9.2 GW. The domestic production of Japanese companies was 3.4 GW, accounting for 37% of the total sales volume in Japan. Japanese overseas PV production and PV imported to Japan was 2.9 GW (31%). In total, 68% of the PV quantity installed in Japan was made by Japanese companies, and mainstream domestic solar power generation was based on Japanese brand products. However, even if a product was actually sold as a Japanese brand, part of the manufacturing represents original equipment manufacturer (OEM) (brand name manufacturer) from other countries. OEMs also exists

Table 5
Where economic benefits of material and components costs occurred [%].

Manufacturing company	Japan			Japan			Overseas			Overseas		
Manufacturing place	Japan			Overseas			Japan			Overseas		
	Japan	Other developed countries	Developing countries	Japan	Other developed countries	Developing countries	Japan	Other developed countries	Developing countries	Japan	Other developed countries	Developing countries
Solar grade silicon (SOG-Si) production												
Metal Silicon	0	3	97	0	3	97	0	3	97	0	3	97
Hydrochloric acid, hydrogen gas, others	22	2	76	0	3	97	22	2	76	0	3	97
Wafer production												
Quartz crucible (silica sand)	71	22	7	0	75	25	71	22	7	0	75	25
Quartz crucible (others)	59	8	33	0	19	81	59	8	33	0	19	81
Silicon carbide (SiC) abrasive grain (silica sand)	71	22	7	0	75	25	71	22	7	0	75	25
SiC abrasive grain (coke)	0	78	22	0	78	22	0	78	22	0	78	22
SiC abrasive grain (others)	100	0	0	100	0	0	100	0	0	0	23	77
Piano wires	37	19	44	0	30	70	37	19	44	0	30	70
Others	100	0	0	14	5	81	100	0	0	0	5	95
Cell production												
Silver paste (silver)	54	27	19	0	59	41	54	27	19	0	59	41
Silver paste (others)	58	22	21	0	51	49	58	22	21	0	51	49
Aluminum paste	100	0	0	100	0	0	100	0	0	0	20	80
Cell production (others)	100	0	0	14	5	81	100	0	0	0	5	95
Module production and assembly												
Tempered glass(silica sand)	71	22	7	0	75	25	71	22	7	0	75	25
Tempered glass(soda ash)	1	1	99	0	1	99	1	1	99	0	1	99
Tempered glass(others)	100	0	0	13	20	67	100	0	0	0	23	77
Aluminum frame (ingot)	24	40	36	0	53	47	24	40	36	0	53	47
Aluminum frame (others)	100	0	0	3	50	47	100	0	0	0	52	48
Sealant	100	0	0	13	7	81	100	0	0	0	8	92
Back sheet	100	0	0	24	26	50	100	0	0	0	34	66
Module production (others)	100	0	0	14	5	81	100	0	0	0	5	95

in Japan as well as in other countries. For example, some Japanese companies sell products under their name that were manufactured by other companies in Japan. In this paper, however, only OEMs from other countries were intended to see an economic influence in other countries caused by the sales from Japanese companies. Hereafter, an OEM in this paper means an OEM from other countries. As the ratio of OEM in the amount of production of Japanese companies was unknown from available data (JPEA, 2017), it was estimated based on data on production by OEM of each major company from Fuji Keizai (2015).[2] As a result of the estimation, 2.6 GW was OEM production in part of 6.3 GW of domestic production. Products manufactured by Japanese companies (both domestically and overseas) and ultimately shipped overseas were 0.5 GW. The share of Japanese companies of the worldwide sales volume[3] was 12% and 8% in consideration with OEM. Fig. 7 shows only silicon type. In Japan, share of silicon solar cells is 92% of whole solar cells sales.

Table 6
Ratio of main equipment cost to equipment cost in each process.

	Equipment cost [Billion JPY]		Ratio of main equipment to cost[-]
	Main equipment	Other equipment/facility	
Total for cell production	38	58	0.55
Ingot	15	23	
Wafer	9	14	
Cell	14	22	
Total for module production	13	20	0.64

Source: Inoue et al., 2017.

3.2. Estimation of retrospectively induced costs, C_{RIEC}

We estimated the economic effect retrospectively induced by domestic installation of crystalline solar cells in Japan. Specifically, as shown in Table 1 (2.2.1), there was a domestic and overseas relationship at each stage, of which only the shipment in Japan was summarized. Fig. 8 sets out the C_{RIEC}. The second and third bars show the costs of monocrystalline and polycrystalline respectively. The lowest bar shows calculation of the cost, including overseas installation by Japanese companies, as a reference value. As in Fig. 6, there are many flows, including overseas products imported to Japan, Japanese companies manufacturing abroad, and Japanese brands manufactured by foreign companies (OEM). Considering this situation, the C_{RIEC} of use in Japan was 1.55 trillion JPY worldwide, of which 63% was the effect brought to Japan. In addition, the economic effect of products shipped overseas by Japanese companies was 47 billion JPY, of which the economic effect in Japan was 18 billion JPY. This reflected the overall amount of benefit to Japan

[2] OEMs in PV manufacturing often manufacture cells, and sales companies often only handle assembly. For this reason, we assumed the production by OEMs primarily at the cell production stage, because the module production stage at the boundary condition in this paper mainly covers the assembly process. According to the JPEA (2017), the Q_{CP} of Japanese manufacturing companies in Japan ($Q_{CP,Jp,\ r=Jp}$) is equivalent to the $Q_{CP,Jp,\ r=Jp}$ estimated from the factory data (Fuji Keizai, 2015). The $Q_{CP,Jp,\ r=Jp}$ is not considered to include OEM amounts. The $Q_{CP,Jp,\ r=Os}$ estimated from the factory data in 2014 was only 240 MW of monocrystalline cells. According to JPEA data (2017), the $Q_{CP,Jp,\ r=Os}$ is 2460 MW in total, so the remaining 2220 MW is estimated to be the amount of OEM for cell production. On the other hand, the total OEM production is estimated to be 2600 MW (47% of silicon cells) (Fuji Keizai data, 2015). The amount of OEM at module production is assumed as 2600 MW - 2220 MW = 380 MW. As a result of these, the OEM proportion of cell production was 91%, and the module was 12%.

[3] Worldwide sales volume in 2014 was 55,935 MW (Fuji Keizai, 2015).

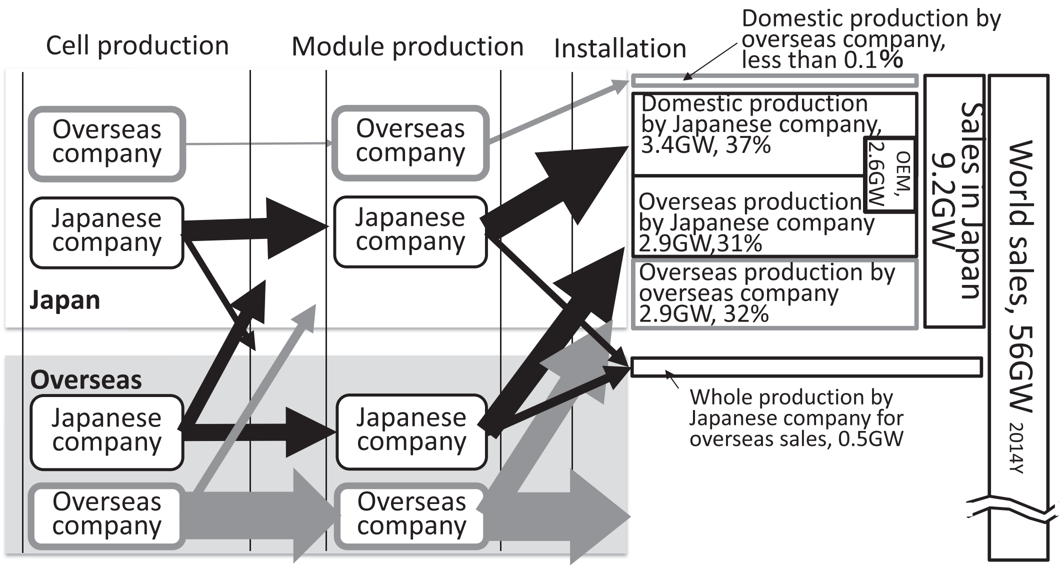

Fig. 6. Simplified flow from production to sale of photovoltaic solar cell systems (Japan case study).

due to the use of solar cells in other countries. A UK research company (Nikkei Technology, 2014) reported that the worldwide PV power generation system and related service market in 2013 was about 59.8 billion US dollars for new introduction of 37 GW (6.3 trillion JPY at a conversion rate of105 JPY/1 USD). Based on that value (although the year differs by 1 year), the economic effect related to Japan was estimated at 1.60 trillion JPY (including overseas shipment), accounting for 25% of the world market. The economic effect of polycrystalline cells is greater than monocrystalline cells. This is simply because the amount of sales and shipment of polycrystalline is 1.7 times larger than monocrystalline. The result comparing the two crystalline cells per output is shown in Fig. 11.

Results by cost type are shown in Fig. 9. The breakdown of C_{RIEC} to Japan showed that C_{eq} was high, 37% of C_{RIEC} to Japan. This is because Japan produces major manufacturing machines and inverters, and supplies them to the domestic market with a high market share. Particularly, the ratio of inverter yields 85% of C_{eq} for Japan, in contrast, just 21% for other countries. The economic effect is expected to increase as an absolute value with increased use of PV on a global scale in future. The C_{eq} may decrease because of improvement in technology and expansion of market share in other countries, especially in companies producing those equipment in developing countries. The share of the sales volume of Japanese companies for inverters in Japan was 91% in 2014,[4] and the world market share was 26% (Fuji Keizai, 2015), but the share in other countries (excluding sales in Japan) was only 0.9%.[5] From the perspective of strength-based future strategies, it is important for mechanical/electrical equipment industry in Japan to further improve the technical level of equipment (e.g., inverters and manufacturing equipment). An existing report (SunEdison, 2011) indicated that breakdowns of the inverter component in the PV power generation system accounted for 51% of the total number of failures in 2008–2010. This highlights the importance of reliability and long life of the inverter component.

Another outstanding feature of the results is that the C_{lb} is large. This is because of high labor costs at the installation stage. There are some economic effects in the C_{mt}. Although the material procurement depends on importing the primary raw material, the added value of the prepared material in Japan compared with the main raw material price was high, indicating that the economic effect on the material production in Japan increased. The involvement of Japanese companies increased as the economic effects related to Japan were calculated, resulting in greater effects in the C_{bs} than those in other countries. Although Japan's cost for installation tends to be much higher than in other countries (IEA-PVPS, 2016), the existence of an intermediate profit was pointed out as a factor of high cost of Japan (Kimura and Zissler, 2016). Though analysis assumes certain amounts of labor costs and corporate profits as the effect of large-scale introduction, it is surmised that the actual labor costs and corporate profits are significantly greater than the calculated value. They may have contributed an economic influence in Japan. However, these economic benefits are temporary, and it is considered to converge to the calculation result of this analysis as the market matures.

Fig. 10 presents a summary by stage (e.g., cell manufacturing and module manufacturing). The C_{RIEC} induced in Japan were small at the manufacturing stage of the cell and module. This may be overcome by technological innovation and cost reduction. The effect is concentrated on the installation stage, 71% of C_{RIEC} to Japan, because the inverter is required for this stage, steel is used for balance of systems, and C_{lb} for installation are high. Higher construction expenses (summation of C_{lb} and C_{bs}) are positive for economic activity in the short term, but are not connected with technology development and should be reduced to promote future diffusion. Of the cost of the economic effect of installation in Japan, 43% was inverter costs, 15% was material costs, and 42% was construction costs. C_{RIEC} to developing countries were high in the manufacturing stage for both cells and modules. In addition, as shown in Table 3, this calculation was used a set unit cost, regardless of the country (excluding costs for transportation). Labor and utility costs in developing countries are expected to be low, and results related to developing countries are likely to be lower than

[4] According to Fuji Keizai (2015), the amount of sales by Japanese companies whose manufacturer names were known among 11470 MW of inverter shipments in Japan in 2014 was 10480 MW; 10480/11470 MW was calculated.

[5] According to Fuji Keizai (2015), among Japanese companies with worldwide shipments in 2014 (41500 MW), 390 MW were for overseas shipments excluding shipment volume in Japan for Japanese companies whose manufacturer names were known; 390/41500 was calculated. Companies whose manufacturer name was known accounted for 3.1% or more of the world market share. Although manufacturer's unknown shipments accounted for 11400 MW, the proportion of Japanese manufacturers was unknown.

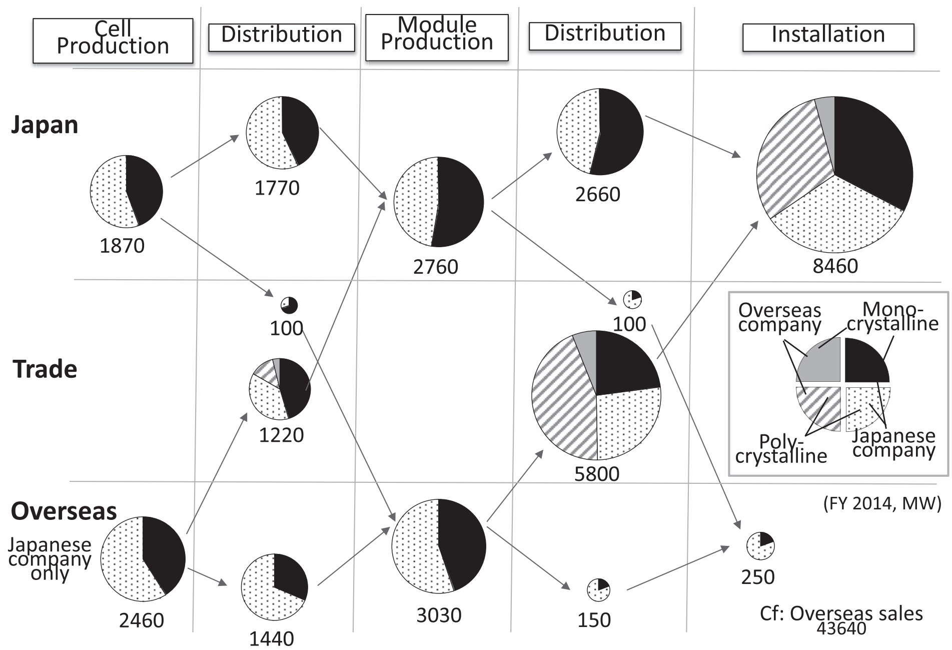

Fig. 7. Detailed flow from production to sale of silicon photovoltaic (monocrystalline and polycrystalline) solar cell systems (Japan case study). Note 1: The total domestic production volume of cells and the import amount of cells do not match the domestic production volume of the module because of inventory adjustments and manufacturing timing differences. Note 2: Production volume by original equipment manufacturer (OEM) mentioned in the text is not shown in the figure. Note 3: The circle in "Overseas" presents only the amount by Japanese company because overseas data cannot be obtained with the same level of precision as Japan's data. Also, because the overseas part is relatively large, it becomes difficult to understand the figure.

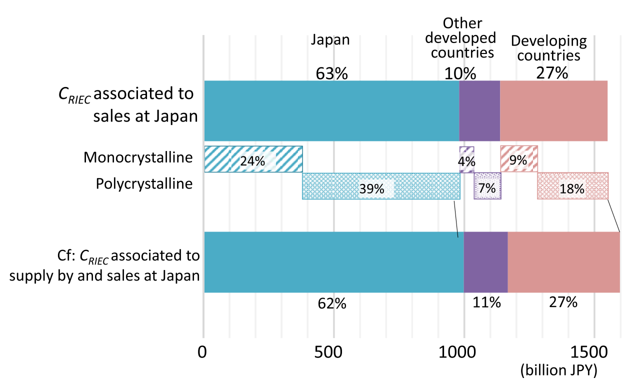

Fig. 8. Retrospectively induced costs associated with supply and sales of silicon solar cell systems in Japan.

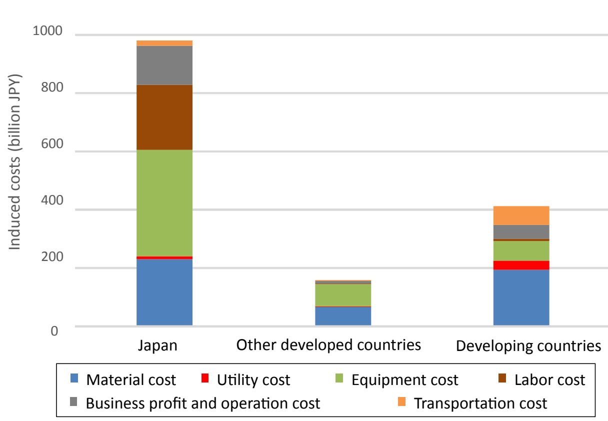

Fig. 9. Retrospectively induced costs associated with sales of silicon solar cell systems in Japan, by cost.

the results reported here.

The primary message is that if the initial costs of the technology rely heavily on other countries or if it is imported from another country, it will be beneficial to that country in the case of a high-cost technology at the site, in the installation and utilization stage. As a further calculation, assuming there was no manufacturer in Japan or Japanese companies in other countries and all domestic installations were imported, the economic effect on Japan would decrease by 0.27 trillion yen. It is not a significant reduction because of the high percentage of impact at the installation stage. As described above, there is a possibility that the merit of C_{eq}, which is currently occupying a significant amount of the economic effect in Japan, may be decreased due to future efforts by developing countries. It is important to consider the case of PV imports from other countries and investments in Japan and overseas regarding the manufacture of cells and modules. This includes corporate acquisitions for cell and module production and focusing on gaining economic effects by R&D and installation of equipment such as inverters and production machinery.

Fig. 11 presents a summary of the breakdown of C_{RIEC} of monocrystalline and polycrystalline Si solar cell sales in Japan. The ratio of material costs in Japan ($C_{RIEC,\ mt,r=JP}$) of monocrystalline was higher than the ratio of polycrystalline, whereas the ratios of monocrystalline costs in other countries were lower. This is because domestic module production ratios of monocrystalline are higher than polycrystalline (domestic production ratio to final shipment quantity is monocrystalline: 46%, polycrystalline: 23%).

Fig. 12 shows the result of sensitivity analysis on how much the change in each cost affects the ratio of C_{RIEC} to Japan. Even if each cost is doubled or halved, the change in the ratio is less than 5%. The biggest changes were labour and material costs; when each cost was doubled, the ratio of C_{RIEC} to Japan increased from 63% to 67% and decreased to 59%. The reason for the small change in the economic effect is that Japanese society related to PV market were mainly benefiting from the Japanese market. It means it tended to

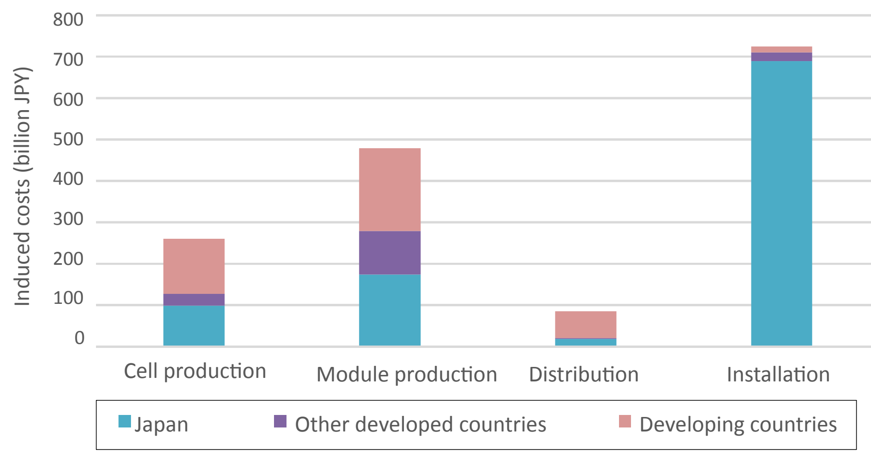

Fig. 10. Retrospectively induced costs associated with supply and sales of silicon solar cell systems in Japan, by stage.

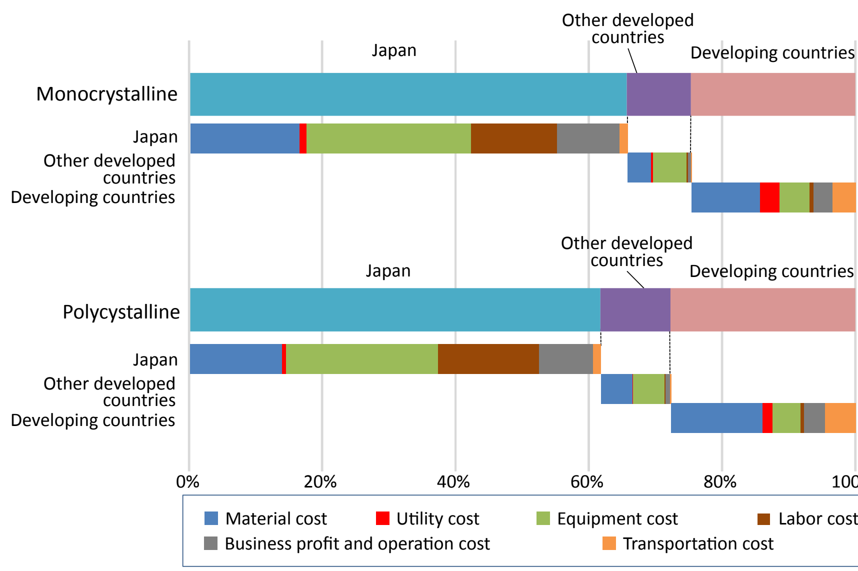

Fig. 11. Breakdown of retrospectively induced costs associated with sales in Japan of monocrystalline silicon and polycrystalline silicon solar cell systems.

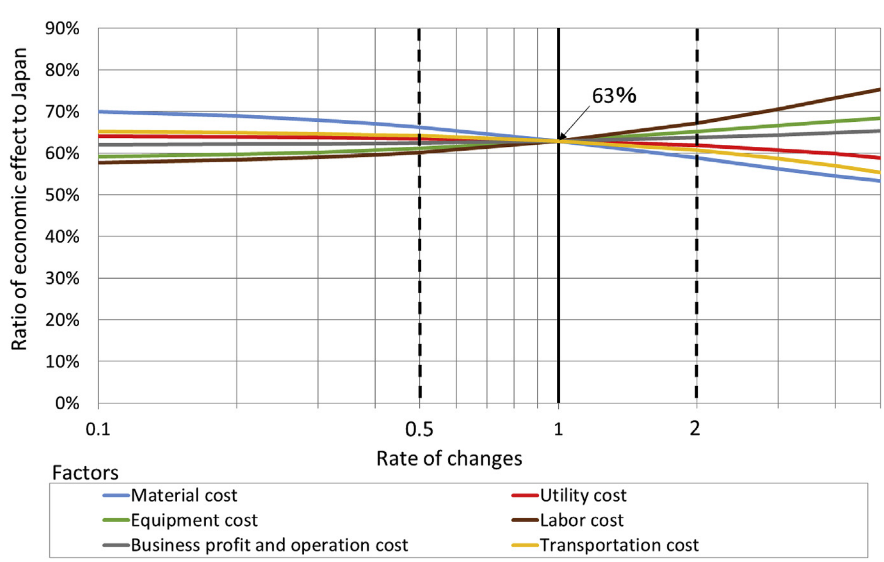

Fig. 12. Result of sensitivity analysis.

be domestically bound in the supply chain. As described in the paper, the Japanese market occupies 50% in the module and 90% in the inverter, while its presence in the world market is almost none. It became clear that Japanese companies had failed to stay updated with globalization in this specific market. To increase the contribution and further disseminate solar power generation technology, it is important for Japan to focus on increasing the worldwide market share by improving inverter and manufacturing equipment technology and reducing their costs.

In our proposed ICA, we considered it important to quantify the reduction of contribution by use of technology, while promoting low carbonization globally through technology transfer and cooperation. Information on economic impacts by country is important to determine to which country the reduction contribution amount belongs. Based on our value chain evaluation for solar power generation technology, the international technology dissemination and suggestions for Japan can be summarized as follows.

- Although various policy supports and technical roadmaps have been actively developed for cells (e.g., based on road maps of Japan, other countries, and international organizations), it will be important to focus on peripheral and manufacturing technology in future.
- Because PV is already technically popular on the market worldwide, it is difficult to regard it as a target technology for development assistance. However, if a PV system is targeted for assistance, inverter and manufacturing equipment will also be expanded as related contribution technologies to improve reliability and long life.
- It is important to consider the degree of contribution of solar power generation technology in the world and contribution by Japanese technology. The influence of materials and equipment in the value chain should be quantitatively evaluated.
- A different discussion may be important, including where the future investment goes, whether it is their own country or other countries, as the global strategy of sustainable industrial development.

4. Conclusion

In the calculations discussed here, we traced worldwide flow as related to Japan for the manufacture and use of solar power systems and estimated detailed retrospectively induced economic costs for Japan, other developed countries, and developing countries. This is a novel approach combining process-engineering approaches with existing value chain analysis. We found that 63% of the total economic effect was brought to Japan by domestic use of solar power systems. Encouraging widespread use of low-carbon or energy-saving technologies may contribute to worldwide reduction of greenhouse gas emissions. Key questions for consideration are how we realize technology use, how it can be made attractive in the market economy, and how we can encourage spontaneous use. It is vital that we promote strategies that will generate economic benefits by taking advantage of each country's strengths. The value chain evaluation method used in this study makes it possible to evaluate this from a novel international perspective, unlike the LCA to date. In individual companies, worldwide optimization may be sought as a management strategy. However, such information was not provided in a way that allowed it to influence technology development policies of the technology concerned. Our results may provide a bridge between technology development and policy, and the method discussed here may become a key tool. In the present study, we limited our evaluation to Japan because of data availability. However, this evaluation method can be applied in other countries. In addition, although we evaluated the economic impact, we intend to evaluate energy consumption and carbon dioxide emissions in future. It is also important that the methodology used in this research is applied to other technologies and to comprehensively study technology development, transfer, and cooperation strategies.

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